A portable energy-sensitive cosmic neutron detection instrument

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The construction and testing of a portable energy-sensitive neutron instrument are described. This instrument has been designed and constructed for the primary purpose of characterizing cosmic-ray neutron fields in the upper atmosphere and in cosmic reference field facilities. The instrument comprises a helium-3 proportional counter surrounded by 15 mm of lead and 140 mm of polyethylene creating a spherical structure with a diameter of 34 cm. The instrument also incorporates 12 boron-coated diodes, six on the outside of the polyethylene layer with six placed within the structure. The dimensions, materials, and arrangement of these in the instrument have previously been optimized with the MCNPX Monte Carlo simulation software to provide a compromise between the requirements of portability and spectral response. Testing took place at several locations and experimental data from the instrument's operation at the high-altitude Jungfraujoch laboratory in the Swiss alps are presented. © *2008 American Institute of Physics.*
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I. INTRODUCTION

Radiation environments exhibit a broad range of characteristics because of the variety of sources that exist and also because of the substances in such environments that can attenuate and modify the primary radiations. For example, nuclear reactors based on the fission process tend to produce radiation environments comprising neutron and γ-ray components, with the neutron component peaked in energy at approximately 0.7 MeV and rarely extending beyond 10 MeV. In contrast, medical radiotherapy environments can yield neutrons as a result of spurious reactions in the materials of linear accelerators and the surroundings. These are usually slowed down very rapidly by surrounding materials to a level at which they are in thermal equilibrium with the environment, thus they are termed *thermal* neutrons with energies around 0.0253 eV. At the opposite end of the energy spectrum, high-energy reactions that occur as a result of, for example, positively charged subatomic particles incident on nuclear targets in a particle accelerator, can spawn neutrons with extreme energies that are dependent, in part, on the energy of the incident particles. A knowledge of the energy spectrum of an environment comprising neutron radiation is important because the radiation weighting factor for neutrons is dependent on their energy.

All of the examples of radiation environments described above are manmade. There are, of course, naturally occurring radiation environments such as that arising as a result of the reactions of cosmic rays in the upper atmosphere. Positive particles of cosmic origin constantly inundate the earth with energies of up to at least 10^{20} eV.[1] The interaction of this radiation with nitrogen and oxygen in the atmosphere yields secondary particles, a significant proportion of which are neutrons. The energy spectrum of this radiation field is distinctly harder than that normally associated with terrestrial environments. The fluence rate of cosmic-ray neutrons increases up to an altitude of approximately 20 000 m (the Pfotzer maximum) beyond which it falls off, as shown in Fig. 1. The earth's magnetic field acts to modulate the fluence rate of cosmic radiation that is incident on the planet's atmosphere. This causes the cosmic-ray neutron fluence rate and energy spectrum to vary as a function of latitude.[2]

Cosmic-ray neutrons pose a threat to modern memory-intensive electronics because the interaction of these particles in semiconductor materials can yield both reversible and irreversible, i.e., soft and hard errors. In some cases, they can result in catastrophic failure of a device or system. This is a particular concern should such electronics be part of an avionic control system as the failure could undermine the operation of the aircraft.

If electronic devices and systems are to be tested in the real environment, access to high-altitude platforms is necessary. These "laboratories" include high-altitude research aircraft and parasitic experiments on commercial aircraft operations. However, the use of such platforms is often expensive as several measurements can be necessary, due to the low fluence rate characteristics of these environments. Furthermore, any variation in the flightpath of an aircraft, or as a result of transient solar activity, can change the field. For

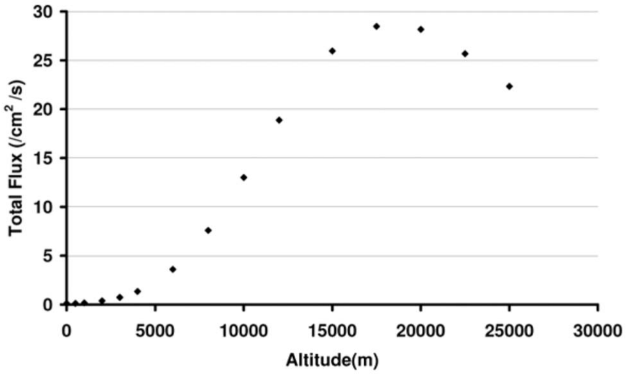

FIG. 1. MCNPX simulation results of the total neutron fluence rate evident at varying altitudes vs altitude.

these reasons, a comprehensive survey of the extensive range of relevant avionic components at high altitudes is widely regarded as impractical. Consequently, researchers can be reliant on the use of ground-based cosmic reference facilities, such as CERF (CERN), the Theodor Svedberg Laboratories (Sweden), TRIUMF (Canada), and Los Alamos National Laboratories (New Mexico). These environments afford greater experimental flexibility than possible at high altitudes, which are cheaper and the fields are often more consistent and better understood.

A key question can arise when comparing ground-based reference field facilities with the environment of interest: How does the spectrum of the cosmic-ray neutron field and that generated at a ground-based reference facility compare? This question can be answered, in part, via simulation using a computational modeling method, such as the Monte-Carlo method. This method has been rigorously tested and is possibly the most convenient approach, especially for environments with energies less than 20 MeV. The use of Monte-Carlo techniques for cosmic-ray neutron energies is also possible although the outcomes are often held with less confidence due to the larger uncertainties in the neutron cross-sectional data at these energetic extremes. An alternative approach is to actually *measure* the field with a neutron metrology instrument. While this might appear to be a superficially easy and obvious solution, given the long history underpinning neutron detection and measurement, this is not the case. The response of most portable neutron spectrometry instrumentation, as discussed in our related studies,[3–5] is limited to energies of less than 20 MeV. Alternatively, Bonner sphere sets have been used to characterize neutron environments on-board high-altitude, dedicated research aircraft.[6] However, these sets have to be extended to spheres of significantly greater diameters to accommodate the higher energies present in these environments. This limits the ease with which such experimental measurements can be made onboard commercial aircraft due to the size and mass of the set necessary. Conversely, because transient solar events are unpredictable and their dynamics are not well understood, it is unlikely that either the modeling approach or an empirical measurement would reflect the neutron spectrum of such an event with sufficient accuracy. A worthwhile comparison of electronic upset cross sections measured in terrestrial facilities with measurements made upon capabilities.

In this paper, we report on the construction and testing of a portable, three-band, cosmic-ray neutron detector that may alleviate some of the difficulties described above. In an earlier publication,[7] the method used to determine the basic geometry of the instrument was described which employed the high-energy Monte-Carlo code MCNPX. In this paper, we describe the construction of the instrument and report on its operation in a specific natural radiation environment at the high-altitude Jungfraujoch laboratory. Our research builds on the extended REM counterprinciple[1,8,9] and the two-band area survey dosimetry principle.[10,11] The innovation in our design is the utilization of boron-coated diodes at two radii within the moderating structure, surrounding a heavy-metal spallation layer and a central proportional counter.

II. DESIGN SPECIFICATIONS

Bonner spheres[12,13] and survey meters operate via the detection of thermal neutrons in a single detector located within a shell of hydrogenous material. The hydrogenous material is necessary to slow the neutrons down to the thermal region in which the response of the central detector is maximized. Variation in the amount of hydrogenous material causes the peak response of the instrument to shift in energy, therefore enabling a degree of spectroscopic control over the response. Charge is liberated inside the central gas-filled detector as a result of the capture of neutrons with, mostly, helium-3 or boron-10 (the latter in the form of boron trifluoride gas) and it is this electrical signal that is subsequently processed.

This fundamental principle has been extended in the design of the instrument described in this work. Unfortunately, the very large homogeneous polyethylene moderators necessary in Bonner spheres designed to cater for the higher energies in cosmic-ray neutron environments are unwieldy. This can be overcome, to a certain degree, by augmenting the standard Bonner sphere design to include some high-Z material surrounding the central detector to encourage (n,xn) reactions.[1,14] A total of 12 silicon diode detectors have been added to the polyethylene moderator structure. Each of these has been coated with a 0.7 mm layer of natural boron. The boron-10 component of this essentially converts thermal neutrons to charged particles which, in turn, are detected in the silicon detector. In the original work performed to optimize the instrument design,[7] lithium-6 was used as a converter on the surface of the photodiode. However, as boron was more readily available, it was utilized in the actual construction instead.

The purpose of the diodes is to optimize the instrument's response in the intermediate and thermal energy ranges. They are arranged in concentric shells with six placed on the perimeter of the sphere, to capture the low-energy neutron component, and six embedded within the moderator structure to capture the intermediate energy component. It is anticipated that an unfolding program will eventually be written which will convert the raw data recorded by the discrete sensors into neutron field information. The design of the instrument is based on the outcome of several thousand simulations using the Monte Carlo simulation package MCNPX.[7,15] The conditions imposed in the original design remit were that the sensor should detect neutrons within an energy range of thermal to hundreds of MeV, should be sufficiently durable to withstand the effects of transportation within a commercial plane and reasonably portable. Parameters varied included the type and thickness of neutron multiplier used to surround the counter, the amount of polyethylene moderator used, and the location of boron-coated photodiodes within the structure. The specifications of the detector were calculated as follows:[7]

- The SP9 proportional counter at the center of the instrument should be surrounded by a 1.5 cm thick layer of lead.
- This structure should be surrounded by a further 14 cm of polyethylene, equating to a total sphere diameter of 34 cm.
- Six boron-coated photodiodes should be placed on the outside of the instrument.
- A further six boron-coated diodes should be placed within the structure at a distance of 14 cm from the center of the counter.

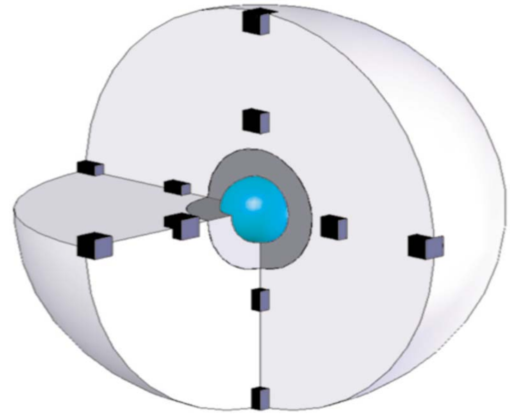

FIG. 2. (Color online) Basic detector design.

III. ASSEMBLY OF THE INSTRUMENT

An SP9 proportional counter with a diameter of 33 mm (Centronic Ltd.[16]) was used as the former to machine the lead spallation shield (Goodfellow[17]) to the required shape. This provides a uniform layer of lead 15 mm thick around the central detector. The SP9 counter is operated with the aid of a Canberra[18] preamplifier (model 2006), which provides the required 900 V potential to bias the gas counter. A 63 mm diameter spherical hole was drilled into the center of a sphere of polyethylene for the detector-lead assembly. The polyethylene has a density of $0.95\ \mathrm{g\,cm^{-3}}$ and the sphere a diameter of 340 mm (John Caunt Scientific Ltd.[19]). A thin bore hole was made in the polyethylene for the stem of the SP9 counter. Finally, six holes of depth 40 mm and diameter 30 mm were bored into the outside of the sphere. These holes were machined equidistantly to maintain the isotropic response of the instrument. The boron-coated photodiodes were then inserted into these holes. Plugs were machined from polyethylene to plug the holes once the inner layer of photodiodes was in place. A schematic diagram of the detector design is provided in Fig. 2. To increase the sensitivity of the instrument and extend the detection range, twelve Centronic OSD 15 T (Ref. 16) photodiodes were coated with boron to provide a sensitizing layer for neutrons. The boron-10 isotope in this layer is exploited to provide reactions of the type

$$ {}^{10}_{5}\mathrm{B} + {}^{1}_{0}n \Rightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\alpha, \tag{1}$$

thus converting incident neutrons to alpha particles, the latter being more easily detected in the silicon layer. Although the process is not 100% efficient, with suitable calibration, it provides an adequate indication of incoming neutrons within a small volume as corroborated before by many groups including Brushwood *et al.*[10] The photodiodes provide a silicon surface area of $15\ \mathrm{mm^2}$ and a footprint of $63\ \mathrm{mm^2}$. The photodiode is integrated into a circular preamplifier circuit fabricated on a printed circuit board (Hybrid Instruments Ltd.[20]) with a diameter of 30 mm. An example of one these is shown in Fig. 3. This small circuit board is attached to a six-wire cable of length 2 m (three grounds, +12 V, −12 V, and a signal line) connected to the main electronics module. Six of the photodiodes were placed within the drilled holes in the sphere at a depth of 40 mm, with the other six located on the outside of the instrument once the holes were plugged with polyethylene.

At the heart of the system is the main electronics module shown in Fig. 4. This is contained in an aluminum box $260 \times 160 \times 70\ \mathrm{mm^3}$, and contains three printed circuit boards designed to perform the essential tasks required in this application. The boards are powered by two switched-mode power supplies powered by the mains, which produce dc potentials of +24 and −24 V. The three circuit boards are

- Regulator board: utilizing a series of regulators to obtain smooth dc voltages of +12, −12, +15, and −15 V used by the instrument.
- High voltage board: employs a high voltage module (EMCO High voltage Corp.[21]) to transform +12 to +900 V, the voltage required to operate the SP9 proportional counter.
- Linear amplifier board: containing 13 line driver circuits used to ensure the signals received from the SP9 counter and the photodiodes are strong enough to travel through the 12 m cable to the logging computer.

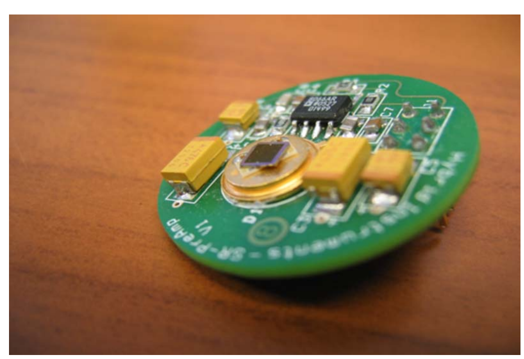

FIG. 3. (Color online) Boron diode design.

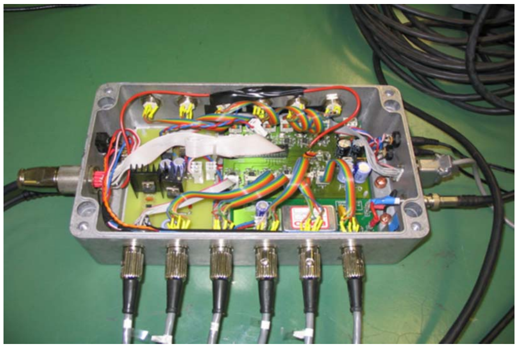

FIG. 4. (Color online) Central electronics box.

The module has several inputs and outputs:

- 12, six pin connections to the photodiode preamps (three grounds, +12 V, −12 V, and 1 signal line).
- Two power input lines (+24, −24 V).
- One 900 V SHV connection to the SP9 preamplifier.
- One BNC connection to receive signal from SP9 counter.
- One 9 pin D connection to power (+24, −24, +12, −24 V, GND).
- One 15 pin connection to convey signals to the software control package.

The module is cooled by a fan to expel hot air away from the circuit through a 40 mm diameter hole in the top of the module. This arrangement was tested and constrained the temperature satisfactorily to within the operational temperature limits of all the components in the module.

Signal processing and data logging are performed within a bespoke LABVIEW environment (National Instruments[22]). This enables easy communication with external hardware devices via several interfaces, such as Universal Serial Bus (USB), General Purpose Interface Bus (GPIB), or, as in this case, data acquisition (DAQ). The 13 signals from the sensors and two grounds are interfaced to the software via a 6062E PCMCIA DAQ card (National Instruments). The DAQ card has a maximum data rate of 500 kHz and a total of 16 input and two output channels. With 13 channels in use, a data rate of 40 kHz is possible per channel, corresponding to a data point recorded every 25 μs. The pulses from the SP9 counter and the photodiodes are 100 μs long and thus the sampling frequency is suitable for the intended point of the current array of data values is below this is per 1000 data points (corresponding to 0.025 s) to prevent an erroneous noisy pattern resulting in the registration of a significant number of false positives. Within the likely test environments, it is highly unlikely that more than one neutron would be registered in a 0.025 s period. A typical screenshot is shown in Fig. 5. The computer used in the operation was a Dell D410 laptop with a Pentium M 1.6 processor and 512 Mbytes of RAM. This proved to be sufficient for the task in hand. The instrument in full is shown in Fig. 6.

IV. TESTING DURING CONSTRUCTION

Testing of the three-band detector has taken place at several development facilities while the instrument has been under construction.

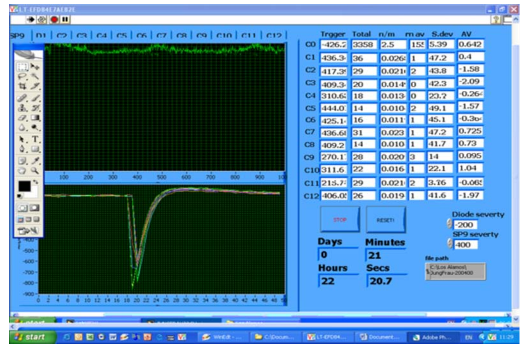

FIG. 5. (Color online) The software interface used to record and log neutrons.

The various discrete sensing elements were tested at the Weapons Neutron Research (WNR) facility at the Los Alamos National Laboratories.[23] At the heart of these laboratories is an 800 MeV linear proton accelerator producing a proton beam which strikes a tungsten target. The resultant neutron beam is collimated and directed into the Irradiation of Chips and Electronics (ICE) House. The spectrum of this radiation field closely matches the atmospheric spectrum with an energy range between 100 keV and 600 MeV with a total fluence rate of $4.1\times10^5\ \mathrm{cm^{-2}\,s^{-1}}$. 1 h in the full strength beam is equal to approximately 1×10^6 h at an altitude of 39 000 ft. The WNR Facility provides neutron and proton beams for basic, applied, and defense-related research, and offers virtually unlimited space in which to place any equipment, as shown in Fig. 7. The energy range of the beam is too high for any of the thermal sensors in the instrument, although the lower energy scatter neutrons were captured by simply placing the various sensors in areas outside of the main beam.

This trial also presented an opportunity to develop and test the software used to record and log the neutron events. Within the ICE house, the test area is separated from the monitoring area by a wall of approximately 2 m in height. The first two of the five results shown in Table I are taken when the counter was within the monitoring area. These two results indicate that when the neutron beam is on in the test area, the fluence rate has increased by 100% in comparison to the background reading. The result with the SP9 counter in the actual beam, actually revealed an almost constant state of saturation. It should be noted that the absolute fluence rate

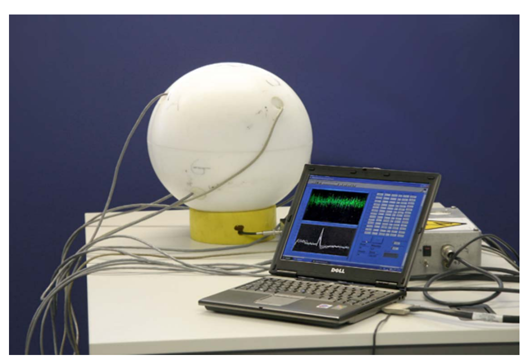

FIG. 6. (Color online) The complete instrument.

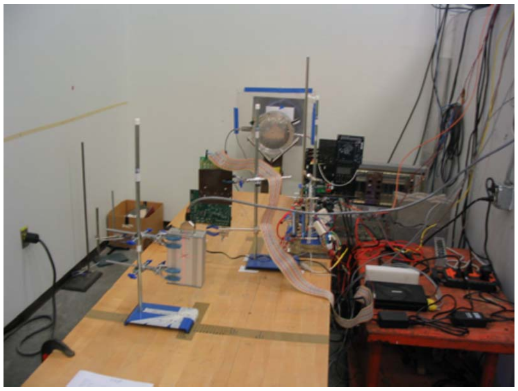

FIG. 7. (Color online) The test area in the ICE house, LANL.

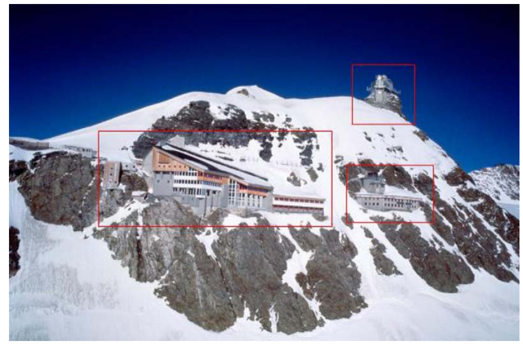

FIG. 8. (Color online) The JungFrauJoch mountain.

values should be ignored as, at this point, virtually any pulse arising from the counter was recorded as a neutron, whereas the majority of these would be almost certainly be due to γ radiation arising as a result of neutron scattering reaction in the surrounding material of the laboratory.

Basic testing of the instrument was conducted at the ISIS facility as part of the SPAESRANE collaboration[24] (Rutherford Appleton Laboratory, Oxford, U.K.).[25] The ISIS facility consists of a proton synchrotron, and several targets, one of which enables neutron production with a measured fluence rate of 6.7×10^4 cm^{-2} s^{-1}. However, unlike at WNR (Los Alamos), the test area was (at time of testing) of very limited size with restricted access to the beam. This meant that the Lancaster instrument could not be used in its completed format due to restrictions on space, although the 13 individual sensors could be, thus restricting the sensitivity range to thermal neutrons. Unfortunately, on this occasion significant levels of noise on one of the photodiode data lines was sufficient to result in cross-talk with other lines and thus no meaningful data were recorded, even from the SP9 channel.

In the course of the development of the Lancaster instrument, several visits were made to the BAE Systems neutron facility (Barrow-in-Furness, U.K.). This facility has several calibrated neutron and γ-ray sources including caesium-137 (662 keV), cobalt-60 (1.1 and 1.3 MeV) and cobalt-57 (12 keV). This resource was especially beneficial to the project as direct comparison could be made with the response of lithium-coated photodiodes (Centronic OSD 7.5 T), fabricated and tested by BAE Systems at the site. The facility consists of a large room with a camera constantly monitoring the output of an oscilloscope in the test area. A small observation room nearby allows the camera output to be monitored without exposure to the radioactive sources.

TABLE I. Early LANL results achieved using the SP9 counter.

Location	Fluence rate (cm^{-2} s^{-1})
In monitoring area (beam off)	0.183
In monitoring area (beam on)	0.363
In test area (beam off)	0.181
In test area (beam on)	3.65
In beamline (beam off)	0.182
In beamline (beam on)	15.33

An americium-beryllium source (Liverpool University, U.K.) was used to test the instrument at incremental stages in its construction to improve the portability of the set up and general operational logistics prior to testing further afield. A weak americium-beryllium source (Lancaster University, U.K.) capable of producing regular low-flux, low-energy neutron output proved to be an essential tool in the development of the Lancaster instrument. Its location allowed an extremely fast test-fix-test turnaround due to its obvious proximity to the development area in the Engineering department.

V. COMPLETE INSTRUMENT TESTING AT THE JUNGFRAUJOCH RESEARCH LABORATORY

The JungFrauJoch research laboratory is located in southern Switzerland, 3580 m above sea level at a mean air pressure of 653 mbars. Extensive research is undertaken at this location in the fields of hydrology, meteorology, glaciology, radiation, astronomy, and cosmic rays. The station consists of several parts such as the railway station, restaurant, accommodation block, and research station itself, all connected by an underground tunnel network. The building at the highest altitude (known as the Sphinx) consists of two large laboratories, a weather observation station, a workshop, two terraces for scientific experiments, and a meteorological cupola. The station is shown in Fig. 8.

From November 2006 until April 2007, the completed three-band neutron-ray detector was installed in the upper laboratory in the Sphinx building. The instrument was monitored constantly on a remote basis via a Virtual Network Connection. This allowed remote real-time data analysis at Lancaster University throughout the 5 months' test period. As a reading for each sensor was recorded every hour, an enormous data set was recorded throughout the course of the instrument's operation with over 48 000 total results recorded to disk. Only a limited number of these can be shown in this publication. The mean fluence rate logged by the assorted sensors is shown in Table II with the average thermal neutron fluence rate for the six photodiodes on the outside of the structure (the outer layer) and the corresponding value for the six photodiodes imbedded 3 cm inside (the inner layer). The average neutron fluence rate recorded at the out-

TABLE II. Total neutron counts and fluence rate for each individual sensor in the instrument over 5 months (raw data) at the JungFrauJoch research station.

Sensor	Total counts (cm^{-2})	Fluence rate ($cm^{-2}\,s^{-1}$)
SP9	999 26	0.008 44
Diode 1	325 13	0.002 75
Diode 2	259 87	0.002 19
Diode 3	187 33	0.001 58
Diode 4	204 53	0.001 73
Diode 5	173 27	0.001 46
Diode 6	147 80	0.001 25
Diode 7	293 47	0.002 48
Diode 8	157 80	0.001 33
Diode 9	185 80	0.001 57
Diode 10	171 83	0.001 51
Diode 11	204 40	0.001 73
Diode 12	336 13	0.002 84
Outer	216 32	0.001 83
Inner	225 96	0.001 91

side of the structure was 0.001 83 $cm^{-2}\,s^{-1}$ compared to an average fluence rate of 0.001 91 $cm^{-2}\,s^{-1}$ recorded at a depth of 3 cm within the instrument.

VI. CALIBRATION

Although the boron-coated photodiodes operate with the same basic principle, the chances of two diodes exhibiting identical responses are negligible due to inevitable discrepancies in the boron layer thickness and consistency. To ensure that the neutron fluence rate recorded with the boron photodiodes and the SP9 proportional counter is normalized, an experiment was set up in the Physics Department of Lancaster University, utilizing an americium-beryllium radioactive source. The 12 photodiodes and SP9 counter were placed in a circular shape of radius 10 cm, with the source in the center ensuring an even fluence rate distribution throughout the sensors' arrangement, as shown in Fig. 9. The sensors were left running for 3 h to afford a comprehensive comparison between them. The total number of neutrons recorded by each of the detectors is shown in Table III, along with the average fluence rate. It appears that in transit from the JungFrauJoch mountain peak, diode numbers 7 and 11 were broken since no neutron response was observed from these sensors in this calibration. The SP9 proportional counter is, as would be expected, the most sensitive of the neutron detection instruments used and accordingly exhibited the highest response here; 150 37 neutrons over the course of 3 h corresponding to a fluence rate of 0.2841 $cm^{-2}\,s^{-1}$

FIG. 9. (Color online) Calibration configuration with 13 neutron sensors each 10 cm from AmBe source.

TABLE III. Total counts, fluence rate, and calibration factor of each sensor when 10 cm from AmBe source.

Sensor	Total counts (cm^{-2})	Fluence rate ($cm^{-2}\,s^{-1}$)	Weighting (%)
SP9	15 037	0.2841	100
Diode 1	131	0.0809	28.46
Diode 2	167	0.1031	36.28
Diode 3	43	0.0265	9.34
Diode 4	11	0.0067	2.39
Diode 5	40	0.0247	8.69
Diode 6	37	0.0228	8.04
Diode 7	⋯	⋯	⋯
Diode 8	41	0.0253	8.91
Diode 9	31	0.0191	6.73
Diode 10	9	0.0056	1.96
Diode 11	⋯	⋯	⋯
Diode 12	143	0.0883	31.07
Outer	429	0.0441	15.53
Inner	224	0.0346	12.17

VII. ADJUSTED RESULTS

Although two of the photodiodes were damaged, the results from the other ten photodiodes and the SP9 counter were adjusted using the calibration results. The normalized results are shown in Table IV. Furthermore, the normalized neutron fluence rate recorded by the centrally located proportional counter is shown in Fig. 10, with similar results shown for the total outer and inner layers of diodes (Figs. 11 and 12).

VIII. CONCLUSIONS

In this paper, we have described the construction of a portable, energy-sensitive three-band neutron detector. Furthermore, we have illustrated how the instrument has been

TABLE IV. Calibration adjusted results from the JungFrauJoch experiment.

Sensor	Norm. fluence rate
SP9	0.008 44
Diode 1	0.009 65
Diode 2	0.006 05
Diode 3	0.016 93
Diode 4	0.072 26
Diode 5	0.016 83
Diode 6	0.015 52
Diode 7	⋯
Diode 8	0.014 96
Diode 9	0.023 29
Diode 10	0.076 92
Diode 11	⋯
Diode 12	0.009 14
Outer	0.022 87
Inner	0.031 07

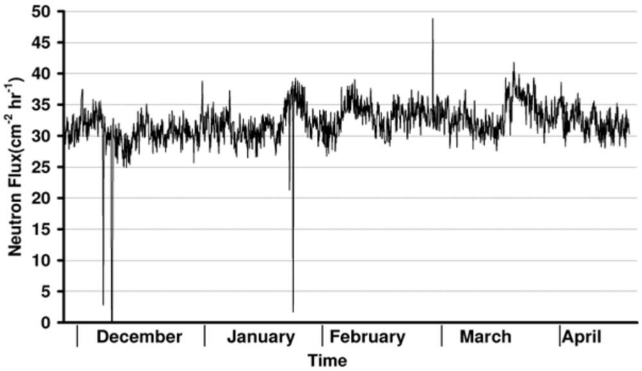

FIG. 10. Total neutron counts received by central SP9 counter.

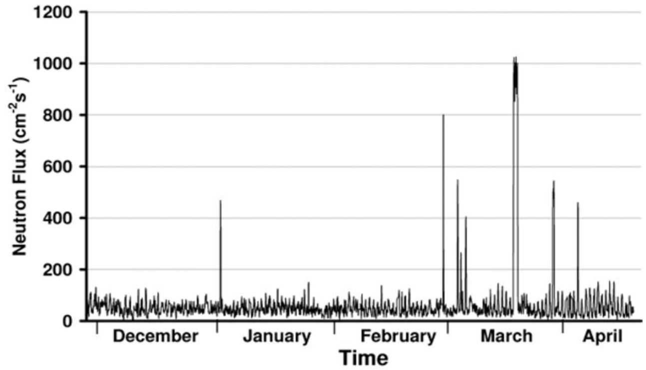

FIG. 12. Total neutron counts received by inner layer of diodes.

tested at international neutron reference facilities. The detector consists of an SP9 proportional counter of diameter 33 mm surrounded with a 15 mm thick layer of lead to encourage spallation reactions. This structure is enclosed by a further 140 mm thick spherical layer of hydrogenous polyethylene designed to reduce the energy of incident high-energy neutrons to a level detectable with thermal capture techniques. 12 photodiodes have been coated with a thin layer of boron to encourage alpha particle emission as a result of thermal neutron capture. Six of these diodes are placed on the outside of the polyethylene structure to capture thermal neutrons with further six located at 3 cm within the layer to detect incoming neutrons of an intermediate energy. The data gathered by these 13 discrete sensors can be combined to produce a neutron field description using unfolding techniques combined with work completed in an earlier publication.[7]

The instrument, at various states during its construction, has been tested at several national and international facilities. These include the Los Alamos National Laboratories (New Mexico), The ISIS facility (Oxfordshire), BAE Systems, the Physics departments at Lancaster and Liverpool Universities, and the JungFrauJoch research station (Switzerland). The results obtained from the first set of trials were carried out to optimize sensor design. The second trial was carried out at the JungFrauJoch research station, to test the completed instrument. The results acquired from the instrument while located at the JungFrauJoch site indicate a normalized fluence

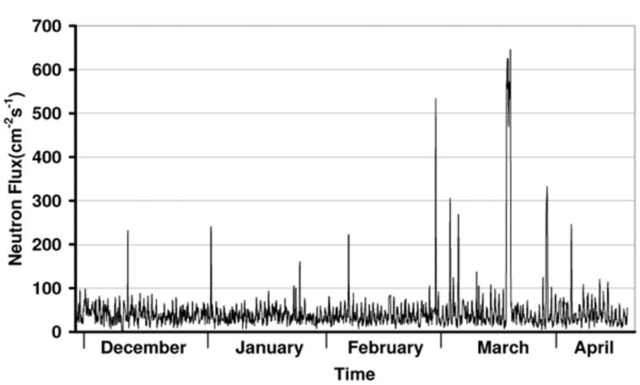

FIG. 11. Total neutron counts received by outer layer of diodes.

rate of 0.0084 of thermal neutrons at the center of the instrument, a normalized fluence rate of 0.022 87 recorded at the outside of the structure and a normalized fluence rate of 0.031 07 recorded at a depth of 3 cm within the instrument.

Unfortunately, the JungFrauJoch research station experiences lengthy power cuts which will obviously render the instrument unoperational for long periods of time, as can be observed in Fig. 10 where for three periods of time, the power was off long enough for null values to be recorded by the instrument. This effect is also observable on Figs. 11 and 12, but is not so obvious due to the proximity of the base line to the *x* axis. Shorter periods of downtime were highly probable throughout the testing period meaning that absolute values cannot be held in high regard. However, as a cut in power would be expected to affect all of the channels, the ratio between the channels should not be affected by this problem. For future work, an uninterruptable power supply will be used.

Large neutron fluence rate peaks were noted at several periods by both the inner and outer layers of photodiodes, most noticeably on the 17th of March 2007. This particular peak is only slight in the result set derived from the central SP9 counter, an approximate rise of 30% above average compared with a rise of around 2500% above average for the inner layer of photodiodes. The neutron monitor based in the laboratory does not feature a peak on this date, indicating a false positive registered by the Lancaster University spectrometer.

As mentioned earlier in the report, an unfolding algorithm has yet to be written to convert the raw data recorded by each sensor, into a neutron field. Until this has been achieved, there is no way to know whether the data recorded by the spectrometer match the traditional theoretical field at this position.

The original aim of this work was to construct an energy-sensitive portable robust cosmic-ray neutron spectrometer. Obviously the failure of diodes 7 and 11 indicates that the instrument is not robust enough to completely satisfy these criteria. However, in future work, we plan to make another version of the instrument with several key improvements:

- Implement an unfolding program to convert the raw data to spectroscopic information.

- Improve robustness of the boron-coated photodiodes through perfected circuit design.
- Implemented wireless connectivity between the diodes and the laptop computer.
- Improved neutron-gamma discrimination.

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